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The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation

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Abstract

Studies have shown that building energy demand in identical dwellings could vary by a factor of three. Differences in occupant behaviour – i.e. purchase, operation and maintenance – have been implicated as a strong source of these differences. The literature suggests that feedback on energy use to building occupants – particularly real-time feedback – can be used to prompt lower operation-related energy behaviours. This is particularly true for thermal demand which, in cold countries, accounts for four times as much energy use as non-thermal demand. However, there is little evidence to support this claim. Further, there are concerns that the actions that allow occupants to lower heating energy use could negatively impact their comfort by lowering indoor temperatures or air quality below acceptable thresholds. We report results from a winter field study that used in-depth energy, environmental and motion sensing to generate real-time context-aware feedback through a smartphone application. Subjective data and clothing levels were concurrently collected through questionnaires. Our results suggest that real-time feedback could lower radiator and room temperatures without significantly affecting occupant thermal comfort. The results also show that real time feedback could contribute to an increase in occupant perceived environmental control (a key variable in the theory of adaptive thermal comfort) while prompting lower heating energy behaviours.

Keywords: Real-time feedback, Occupant behaviour, Thermal comfort, Adaptive model

1. Introduction

The domestic sector accounts for approximately 24% of the world's energy consumption [1]. In cold climates, 32% of this consumption, on average, is due to space and water heating [1]. However, in highly industrialized countries, heating energy use represents a far higher proportion of the domestic energy demand, *e.g.* 57% in the UK [2].

Building space heating energy consumption depends on several physical factors:

- Geographical factors i.e. the specific local climate and location (rural, suburban or urban);
- Building characteristics i.e. the building type, the building thermal properties (which depend on infiltration, insulation, orientation, glazing, etc.) and the floor area;
- Efficiency of the space heating system used (gas central heating, district heating, etc.).

Non-physical factors such as economic and social factors also have a strong role to play but, since they are more difficult to quantify, little is known about the magnitude of their effects which are often neglected when estimates of building performances are made. The energy behaviour of building

44 users¹ represents the expression of these non-physical factors which act as underlying drivers and
45 antecedents of occupant actions.

46 Recent research has highlighted the potential impact on heating energy use arising from differences in
47 occupant behaviour [3-6]. For example, occupant characteristics and behaviour have been shown to
48 be responsible for 4.2% of the variation in space and water heating energy consumption in the Dutch
49 residential stock [7]. Similarly, in the emerging domain of domestic energy literacy² research, several
50 studies have examined the impact of increasing literacy on electricity-related behaviours [8-11].
51 However, few studies have investigated its effect on the arguably more important topic of heating
52 energy consumption [12]. Further, whilst some studies have begun to focus on the impact of
53 information dissemination on occupants' heating energy use [13-15], to our knowledge, no studies
54 have investigated the effect of real-time context-aware feedback on occupant heating behaviour,
55 specifically thermal adaptation and comfort. Understanding the links between feedback, behaviour
56 and subjective comfort is important if we are to effectively influence energy-saving behaviour since
57 perceived reductions in comfort are a major impediment to end-users accepting feedback and advice
58 [16]. This paper sets out to address this important gap by investigating the effect of *real-time* and
59 *context-aware* feedback on occupants' adaptive actions, thermal comfort and perceived
60 environmental control in the context of their heating energy use.

61 In a recent critical review on the efficacy of feedback, Buchanan has outlined the importance of the
62 "human factor" when designing effective feedback strategies [16]. According to Buchanan [16],
63 feedback must be designed with a user-centred approach in order to "enable users to readily
64 understand the habits and routines that generate their household energy patterns and thus make
65 more concrete the viable energy saving actions available to them". Following the indications of
66 Buchanan, we adopted *real-time* feedback since many studies in the domain of electricity use have
67 shown that immediacy increases salience and user engagement, and also provides the potential for
68 greater energy savings [17-19]. Furthermore, *context-awareness* was also considered necessary
69 because, in order to show "available and viable energy saving actions", feedback must respond to the
70 context in which the energy behaviour has occurred [16].

71 **2. The dynamic model of thermal adaptation**

72 The *building indoor climate* (e.g. humidity, dry-bulb temperature, radiant temperature, air speed) and
73 occupant *personal physiological factors* (e.g. age, gender, health situation, clothing, activity level)
74 affect occupant thermal situation producing different *environmental stimuli* (Figure 1). If we imagine
75 two occupants ideally exposed to the same *environmental stimuli*, their thermal perception is not the
76 same but depends on their subjective *thermal expectations and preferences* (Figure 1). In fact,
77 according to the adaptive model of thermal comfort [20, 21], thermal comfort is not merely the result
78 of a body's thermal balance but is the outcome of a continuous process of adaptation involving three
79 types of self-regulatory actions: physiological, psychological and behavioural.

¹ In this study, we define energy behaviours as those conscious or unconscious actions taken by occupants that result in energy consumption in the building. See Section 2 for examples under behavioural adaptation.

² "Energy literacy" in this context may be defined as occupants' awareness of the impact of their individual behaviours on building energy use.

80 Physiological adaptation is any physiological alteration which happens in response to ambient thermal
81 changes [22]. According to Brager and De dear [20], for the conditions and the activities typically
82 encountered in residential and office buildings the slow process of physiological acclimatization has
83 only a minimal influence on the thermal experience and, therefore, only psychological and
84 behavioural adaptation affect occupants' thermal acceptability.

85 Psychological adaptation includes any psychological reaction to sensory information (e.g. habituation,
86 relaxation of thermal expectations, gradual change of preferences, etc.) [23]. Many recent studies
87 [24-27] have tried to identify and quantify the role of *cognitive and psychological factors* in the
88 process of psychological adaptation (Figure 1); those factors include:

- 89 • perceived environmental control,
- 90 • personal beliefs and cultural values,
- 91 • past thermal experiences,
- 92 • habits,
- 93 • perceived rewards and benefits:
 - 94 - in terms of comfort/health
 - 95 - monetary

96 In particular, the literature highlights that occupants' perceived ability of environmental control is a
97 key psychological variable in defining occupants' thermal expectations [21, 28-31]. High perceived
98 levels of control have been found to positively influence both thermal satisfaction [28, 32, 33] and
99 productivity [34]. Occupants' perceived control depends on *building contextual factors* i.e. on the
100 availability, accessibility and transparency of means for exerting adaptive opportunities in buildings
101 (e.g. the presence of openable windows). Since people in homes have more possibilities for thermal
102 adaptation and have higher levels of perceived control, they are generally more satisfied with their
103 environment than in their offices [35]. Several studies have also demonstrated that open plan offices
104 are the environments with the lowest acceptance among their occupants [35]. This is due to the
105 limited adaptive opportunities available as well as to the low perceived levels of environmental
106 control.

107 Behavioural adaptation refers to all the conscious or unconscious actions that, when the
108 *environmental stimuli* are perceived as discomforting, a person can take in order to modify the
109 building indoor environment, their personal situation or both of these (Figure 1). This is in agreement
110 with the fundamental precept of the "adaptive model": "if a change occurs such as to produce
111 discomfort, people react in ways which tend to restore their comfort" [36]. Of the three forms of
112 adaptive opportunities, this is the one in which the occupants have the opportunity to play an active
113 role. Adjustments are both personal³ and environmental⁴ and their availability, ease and effectiveness
114 depends on *building contextual factors* [29]. This is shown in Figure 1.

3Personal adjustments include:

- putting on/taking off clothing,
- changing activity level (e.g. having a siesta in the hottest moment of the day, taking a walk inside or outside, starting cooking),
- changing posture of the human body (e.g. curling up/cuddling up),
- moving to a different location (e.g. going to bed, visiting a friend),
- taking in hot/cold food or drinks,
- taking a hot bath/cold shower.

4Environmental adjustments include:

- modifying shadings,
- switching on the fan or the air-conditioner, turning up the thermostat, lighting a fire,
- opening/closing windows or doors,

Therefore, *building contextual factors* have an impact on both behavioural and psychological adaptation. The work of O'Brien [37] identifies the following main *building contextual factors* as external drivers of occupants' thermal adaptation in office buildings:

- occupancy period,
- availability of personal control (*e.g.* is there a window in the room?),
- accessibility of personal control (*e.g.* is the window close to the occupant? is the window openable? to which degree?),
- complexity and transparency of automation systems,
- presence of mechanical/electrical systems,
- view and connection to outdoors,
- interior design,
- socio-cultural constraints (*e.g.* dress code in office buildings, household composition in residential dwellings),
- visibility of energy use.

For the case of residential buildings we need to add economic factors (i.e. the operating costs of heating and cooling). A study conducted in Taiwan observed that air conditioning was used sporadically in homes where opening of windows was the preferred means for controlling indoor conditions, while in offices air conditioning was always on [38]. This study shows that the operating costs of air conditioning have an effect on occupants' thermal adaptation making them largely use air conditioning when money is not their concern (i.e. in their office).

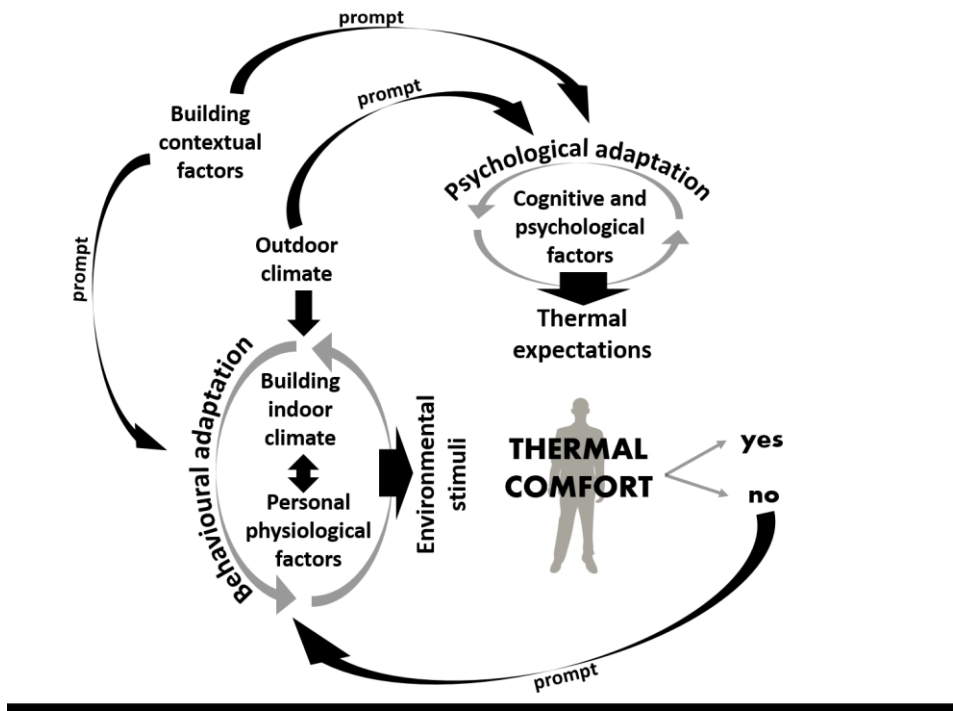


Figure 1 The dynamic model of thermal adaptation

- drawing curtains,
- indirectly modifying heat gains turning on appliances (*e.g.* TV, laptop).

Real-time and context-aware feedback reshapes the building contextual factor “visibility of energy use”. In order to be effective, they should be able to affect occupants’ psychological adaptation (i.e. their thermal expectations and preferences) and prompt “good” energy behaviours (Figure 2). Occupant thermal adaptation can lead to high or low energy consumption depending on how the drivers are affected. In this context, we characterize a “good” adaptation as one resulting in a low heating energy use. For example, if the result of an adaptation would be setting the thermostat at 23°C, wearing shorts and t-shirt and opening the window to generate breeze then this adaptation would be considered “bad”.

The aim of this work is to detect and quantify changes in occupants’ psychological factors (perceived environmental control), level of “good” behavioural adaptation (clothing and ventilation rates) and thermal comfort (neutral temperatures) as a result of the feedback intervention.

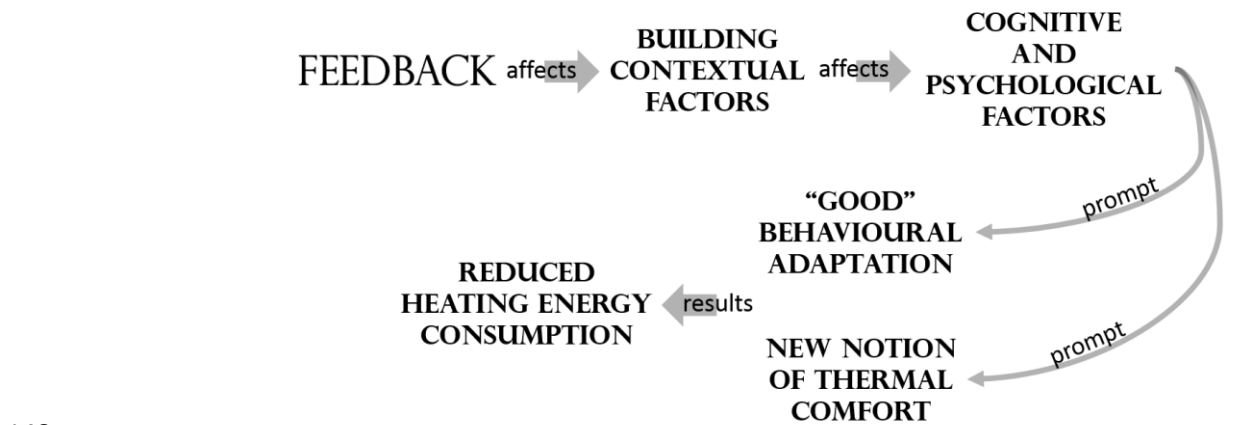


Figure 2 The effect of feedback on heating energy use

3. Methods

3.1 Participants

The experiment monitored 15 volunteer subjects occupying near-identical single-occupancy rooms on the university of Bath campus (see Section 3.3). The participants signed a consent form at the beginning of the study in which they were assured that their data were treated confidentially. They were all first year undergraduates (18-year-old students) with a male-female gender ratio of 1.14 (male=8, female=7). They were of various nationalities, but all were European. At the time of the experiment, all the students had lived in their rooms for about 6 months.

3.2 Experimental procedure

The field study had an overall duration of six weeks, divided into two phases of three weeks each. The first phase (control phase) consisted of monitoring the student rooms, with no feedback. In the second phase (experimental phase), students were provided with feedback via their smartphones, with a specially developed in-house application (Figure 5). The experiment started on the 16 February 2015 and ended on the 29 March 2015.

3.3 Monitored rooms

The 15 monitored rooms are part of three neighbouring residential blocks, on the University of Bath campus. The three buildings are naturally ventilated and are identical in terms of exposure and buildings characteristics. In each of the three buildings the source of heating is a natural gas boiler. The heating schedule was regulated by the estate manager but remained the same during the 6 weeks for the 3 buildings. Dimensions and type of furniture in the rooms are all nearly identical. Each room has a floor area of about 8m² and contains a waterborne radiator with a thermostatic valve. Students were therefore allowed to adjust their valve and also to set the valve to zero.

3.4 Physical measurements

Each room was equipped with environmental and motion sensors reporting every minute to a university-hosted database, allowing in-depth real-time monitoring of the rooms. The sensors consisted of an air dry bulb temperature sensor, a relative humidity sensor, a CO₂ sensor, a temperature sensor fitted on the radiator and a PIR infrared motion sensor to detect room activity (Table 1). Environmental sensors were placed at a height approximately of 1m from the floor. They were placed where they could not be hit by direct solar radiation, at least one meter away from the radiators and not less than half a meter away from any wall (Figure 3).

Table 1 Instrumentation details

Parameter	Range	Accuracy
DS18B20 temperature sensor (used for both air and radiator surface temperature measurements)	-10 – +85°C	±0.5°C
RHT03 humidity sensor	0 – 100%	±2%
K30 Senseair CO ₂ sensor	0 – 5000ppm	±30ppm
HC-SR501 PIR Infrared Motion Sensor	120°, 0 – 7m	n.a.

We did not continuously measure radiant temperatures and air velocities. The reduced dimensions of the room did not allow us to place two additional sensors to the three already employed. However, an in-depth inspection of the rooms during the sensor installation visits allowed us to exclude the presence of human-noticeable high air velocity and radiant asymmetries. So, we could disregard these two parameters for the analysis of comfort conditions.

Outdoor atmospheric conditions were recorded at a weather station located on the roof of a building, approximately 200m from the student dormitories.



CO2 sensor
Temperature, humidity and PIR motion sensors
Temperature sensor

Figure 3 View of the residential blocks (left) and of a typical student room (right) showing the positioning of the sensors.

3.5 Psychological measurements

Students were asked to fill two thermal comfort questionnaires per day after being in their room for at least 30 minutes. In the first three weeks, the questionnaire was in a paper format and each student indicated the exact date and time when the questionnaire was taken. In the last three weeks the questionnaire was given through the smartphone application and, therefore, the date and time were automatically recorded. This enabled the collection of 624 valid questionnaires. Each participant provided between 14 and 66 questionnaires, for an average of 42 questionnaires per student.

The daily questionnaire was adapted from ASHRAE [39] and ISO 7730 [40] and included the information reported in Table 2.

Table 2 Daily questionnaire

Current clothing	Clothing items and corresponding insulation values were adopted from both ASHRAE [39] and ISO 7730 [40] standards.
Activity level in the previous 30 minutes	3 possible levels of activity could be chosen [41].
Thermal sensation vote (TSV)	Measured on the ASHRAE seven-point Likert scale.
Thermal preference vote (TPV)	Reported on Nicol's scale: -1 (much cooler), -0.5 (a bit cooler), 0 (no change), 0.5 (a bit warmer), 1 (much warmer).
Thermal acceptability vote (TAV)	Reported in the scale: 1 (clearly acceptable), 2 (just acceptable), 3 (just unacceptable), 4 (clearly unacceptable).
Perceived air quality	

At the end of the first and second experimental phases, students were asked to fill an additional questionnaire designed to measure overall satisfaction with the room and perceived environmental control (see Table 3). The aim was to detect changes to these responses as a result of the feedback.

Table 3 Additional questionnaire

Satisfaction with the thermal environment	In general how do you find the overall thermal environment in your room? Very dissatisfying (1), slightly dissatisfying (2), acceptable (3), rather satisfying (4), very satisfying (5).
Overall humidity sensation	In general how do you find the overall humidity sensation in your room? Very dry (1), slightly dry (2), neutral (3), slightly humid (4), very humid (5).
Overall perceived air quality	In general how do you find the overall air quality in your room? Very dissatisfying (1), slightly dissatisfying (2), acceptable (3), rather satisfying (4), very satisfying (5).

Perceived level of control	<i>How well do you feel you can personally control the temperature in your room? No control (1), light control (2), medium control (3), high control (4), total control (5).</i>
	<i>How well do you feel you can personally control the air quality in your room? No control (1), light control (2), medium control (3), high control (4), total control (5).</i>

Student satisfactions levels before and after the feedback are reported in Table 4, Table 6 and Table 5 for each student. Students' levels of overall perceived control before and after the start of the feedback are reported in Table 8.

3.6 The application

The smartphone application developed for this study is shown in Figure 5. It was developed using the Ionic framework [41] allowing the software development to be deployed on both Android and iOS platforms (since there was a 50:50 split between these operating systems within the recruited occupant sample).

There are a number of ways to design feedback interfaces. In previous works we have shown that the design of the feedback system could have a significant impact on how well a feedback system performs, although the simple act of providing feedback itself has an effect on occupant behaviour [42, 43]. Since the optimal design of an interface is not the focus of the present work, we followed the main indications given by Lohr [44] which suggest:

- to keep clear the background and foreground distinctions in order to make the display visible;
- to organize the interface elements into easily distinguishable and comprehensible sections.

Air temperature is a key parameter for both thermal comfort and heating energy consumption and, therefore, is the content of the first two sections of the application (respectively current and mean daily temperature information). Furthermore, since social comparison can be a strong motivating factor especially in a student environment [10], a comparative element (mean daily room temperature of the other students in the residential block) was introduced to further promote behavioural changes. In the third section of the application, we provided students with a bar chart of today building heating energy cost compared to the previous day ("yesterday"). Finally, since historical feedback has been found to be easily understandable and useful for users [18], in the fourth section we introduced a seven-day overview of daily building heating energy costs.

The application uses real-time data and a set of heuristic rules to produce the following energy savings tips:

- If Friday:
The weekend is coming! Remember to turn off the radiator (by adjusting the valve to zero) if you don't plan to be in your room.
- If between 8PM and 10PM:
Do you feel cold when you go to sleep? Rather than turning up the radiator have you tried wearing a heavy pyjama or using extra blankets? Drawing your curtains can also help to keep the heat in!
- If $\text{CO}_2 < 600$ ppm:
Oops! You might have opened both your window and door, which means that if the radiator is on, you are heating the outside air! If you opened these because your room was feeling stuffy, then remember to close them back quickly to save energy.
- If $\text{CO}_2 > 1800$ ppm:

241 Your room is getting stuffy! Open your window for a while and get some fresh air! Remember to close
242 it back though as otherwise you are just heating the outside air!

243 • If room temperature > 21 °C:

244 Your room temperature is more than 21°C at the moment. Most people find this quite warm. Turning
245 down your radiator would help save energy. If you still feel cold, have you tried wearing warmer
246 clothes instead?

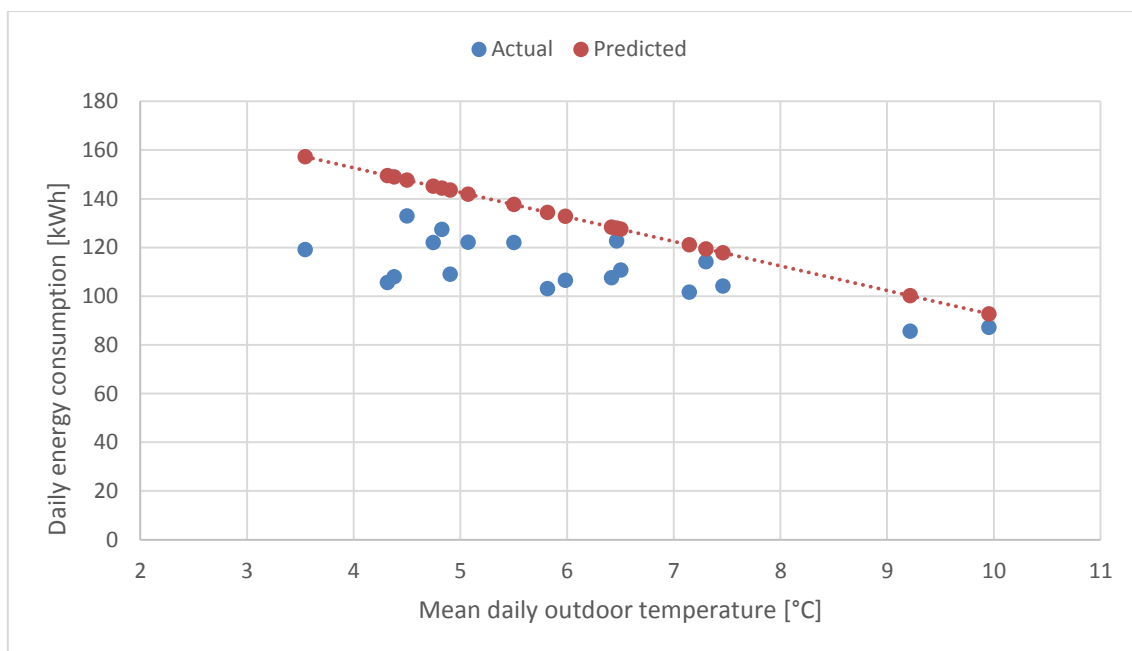
247 The heuristic feedback was only based on real-time measurements of room temperature and room
248 CO₂ concentration; it was not possible to use the measurement from the PIR sensors since some
249 students accidentally covered them up.

250

251 **3.7 Monetary rewards**

252 In a domestic setting, the reduction of energy consumption directly impacts fuel bills and can be a
253 powerful motivating factor for undertaking energy saving measures. However, in a university setting,
254 students do not normally pay for their actual consumption directly since fuel bills are often bundled
255 into the accommodation cost. To simulate as closely as possible the domestic setting in our study,
256 students were rewarded for their energy saving with an amount of money proportional to the energy
257 saved.

258 Using the energy measurements of the previous 4 months (from 1 October 2014 to 31 January 2015)
259 the daily energy consumption of each residential block was weather-corrected using a linear
260 regression model (red line in Figure 4). Energy savings were therefore calculated as the difference
261 between the daily predicted (red dots in Figure 4) and actual (blue dots in Figure 4) energy
262 consumption.

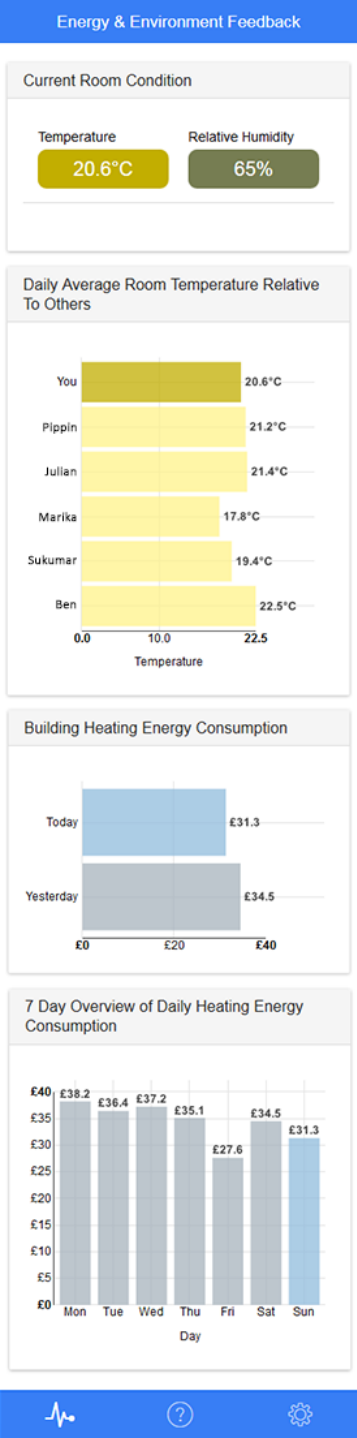


263

264 *Figure 4 Actual and predicted daily energy consumption for a monitored residential block at different mean daily outdoor*
265 *temperatures*

266 An artificial gas tariff (of 0.2 £/kWh instead of the 0.03 £/kWh typically paid by domestic consumers)
267 was used for the monetary rewards to make the cost-feedback more salient due to the short duration
268 of the feedback phase. This tariff is the same as the one used for calculating the daily energy costs
269 shown in the application (Figure 5). The tariff value was obtained from an estimation of plausible
270 expected energy savings in a study of this duration that would result in meaningful pay-outs to the
271 participants. This was based on an approach already established in previous works, see *e.g.* [43]. In
272 real homes, the opportunity to contextualise savings against an entire heating season would be
273 available, allowing the numbers to be more meaningful by using real tariffs. Indeed, at the time of
274 writing, the method presented in this study is used to produce messages in real homes but using real
275 tariffs resulting in meaningful savings for each household over the heating season. We will report on
276 this in due course. Furthermore, real tariffs can be complicated; for example, most tariffs would also
277 include a standing charge, which is hard to capture in a study of this kind. However, we recognize that
278 tariffs could play an important role in designing feedback strategies and that, in particular, variable
279 rate energy tariffs are expected to become more important in the future. Therefore, further work will
280 be needed to understand if and how variable tariffs can affect behavioural changes.

281 Students were only rewarded at the end of the experimental phase (i.e. at the end of the six weeks).
282 They earned an average of 7 pounds each during the three weeks (min = 3.5£, max = 10.2£).



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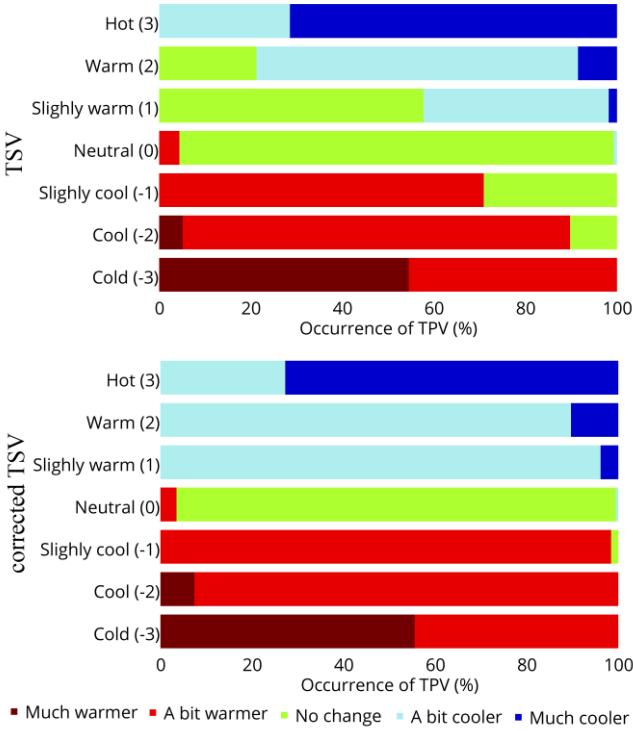
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Figure 5 Screen of the application

285 **4. Results and discussion**

286 **4.1 Analysis of the comfort conditions**

287 The heating energy behaviour of building occupants is directly linked to its primary “product”:
288 occupant thermal comfort. Therefore, an analysis of adaptive thermal comfort is the main focus of
289 this work. In this Section we describe the overall comfort conditions in the 15 monitored rooms and
290 we introduce the variables used for analysing the effects of feedback on occupants’ subjective
291 comfort conditions.



292
293 *Figure 6 The two graphs show the distribution of TPVs (Thermal Preference Votes) expressed as % for different uncorrected*
294 *(top) and corrected (bottom) TSVs (Thermal Sensation Votes).*

295 The distribution of Thermal Sensation Votes (TSVs) and Thermal Preference Votes (TPVs) is shown in
296 Figure 6 (top). Occupants report ‘no change’ thermal preference for ‘Warm’, ‘Slightly warm’, ‘Neutral’,
297 ‘Slightly cool’ and ‘Cool’ thermal sensation votes. In particular, it can be noticed that there is a
298 prevalence of ‘no change’ votes on the warm side of the thermal sensation. This shows that thermal
299 neutrality does not always correspond to the preferred thermal sensation and that people prefer
300 warm thermal sensation when is cold outside (i.e. in winter). This fact is known as the “semantic
301 artefact hypothesis” [20]. If an occupant is ‘slightly warm’ and does not want to change his thermal
302 environment then his/her ‘slightly warm’ sensation, at this moment, implies comfort. The same
303 reasoning applies for ‘warm’, ‘cool’ and ‘slightly cool’ thermal sensations.

304 In order to take into account this fact and in order to make more robust the thermal comfort analysis
305 of the next Section, *non-neutral ‘no change’ votes* are re-defined as *neutral* for the cases when an
306 ‘*acceptable*’ thermal vote is expressed. Doing so, a new distribution for the corrected TSVs and the
307 Thermal Preference Votes (TPVs) is obtained in Figure 6 (bottom). In this new distribution 99% of the
308 *non-neutral ‘no change’ votes* have migrated from the warm and cool side of the thermal sensations

to the central neutral category; this is due to the fact that 99% of the *non-neutral 'no change' votes* are also *'acceptable' thermal votes*.

In order to further demonstrate the validity of the post-survey elaboration of the thermal votes, TSVs and corrected TSVs are shown together with Thermal Acceptability Votes (TAVs) in Figure 7. For the corrected TSVs there is a reduction of *'clearly acceptable' votes* on both warm and cool side of the thermal sensations; this means that *'clearly acceptable' votes* migrate from the warm and cool thermal sensation sides to the central neutral category.

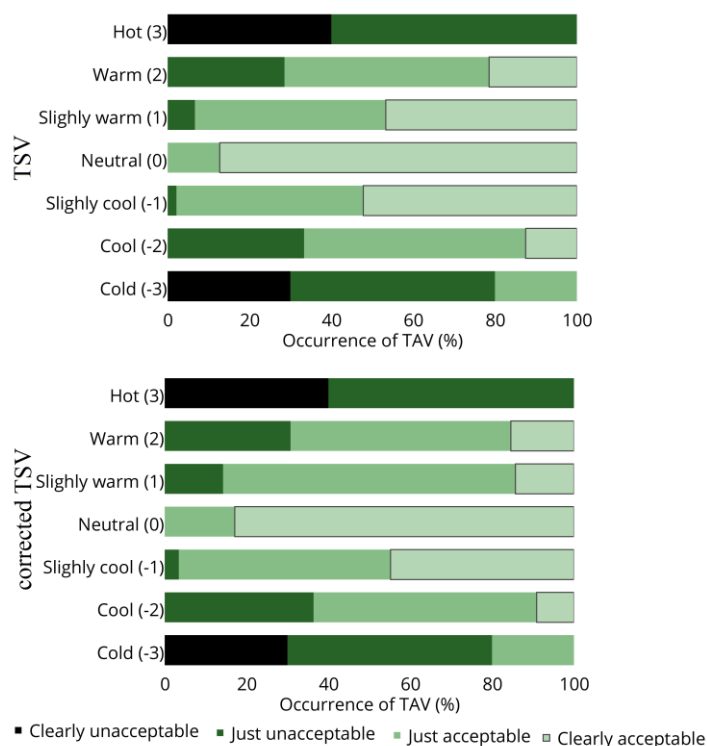


Figure 7 The two graphs show the distribution of TAVs (Thermal Acceptability Votes) expressed as % for different uncorrected (top) and corrected (bottom) TSVs (Thermal Sensation Votes).

According to the ISO 80% acceptability criterion, a thermal environment is regarded as comfortable when 80% of the occupants are feeling between 'slightly cool' and 'slightly warm' [40]. According to this criterion and considering the corrected TSVs, students were comfortable 87% of the occasions. This demonstrate that the rooms can be regarded as thermally comfortable. When considering only the neutral votes (corrected TSV = 0), students were comfortable 69% of the times. The percentage of neutral votes for each student varied from a minimum of 36% to a maximum of 91%. This shows that the level of thermal acceptance varied largely among the different students.

4.2 The effects of feedback on physical variables

The PIR sensor did not work in all the rooms since some students accidentally covered it. Therefore, occupancy profiles were defined based on the indoor CO₂ concentration and then, in order to check the accuracy of the estimation, inferred occupancy profiles were compared with the PIR data for rooms where measurements were available (Figure 8). When comparing the PIR data with the CO₂ profiles, it was evident that if students were going out the room, CO₂ was always decreasing due to air movement through the window and the door. Therefore, following a similar approach of [45], we

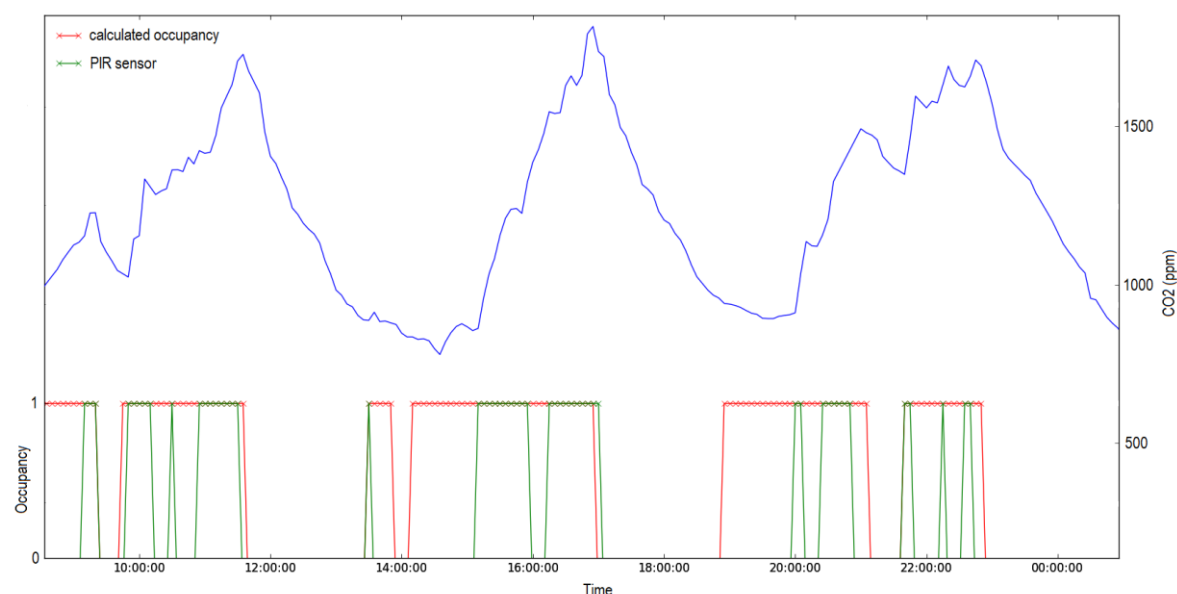


Figure 8 Calculated occupancy profiles based on CO2 concentration

For the analysis, students were sorted into two groups according to the number of questionnaire they filled in during the feedback period. During this period, the questionnaire was integrated in the application and, therefore, a low number of questionnaires can be associated with a low interaction with the app. However, it is not possible to confirm this since we did not explicitly measure the number of viewings of the application. Group 1 includes students that, during the feedback period, filled in more than 13 questionnaires (an average of 20 questionnaires each during the experimental phase). While students of Group 2, in the same period, filled fewer than 8 questionnaires each (an average of 7 questionnaires each i.e. 1 every 3 days which is very low compared to the original requirement of 2 questionnaires per day). Finally, one student whose room was monitored for the 6 weeks did not receive any feedback since his smartphone was not compatible with the developed application.

The average outdoor temperature during the first three weeks was 5.8°C. During the last three weeks it slightly increased to 6.2°C. Since the heating schedule remained the same, room air temperatures were expected to increase. Room temperature slightly increased for student no. 15 of Group 3 who was monitored for the six weeks but did not receive any feedback; while, for all the students of Group 1 (with the exception of students no. 1 and 2) room air temperatures decreased (Table 6). For students no. 1 and 2 (Group 1a) the temperature increase was due to the stricter control of window opening (their mean room CO₂ concentration increased respectively by 22% and 26%). This fact is confirmed by the decrease of radiator temperatures for both students during the last three weeks.

Therefore, unlike Group 2, all the students of Group 1 tried to save energy by lowering their radiator settings (Figure 9). However, they responded to the lower radiator temperatures through different adaptive responses (Figure 10):

- through a stricter control of window opening (Group 1a);
- by wearing more clothing (Group 1b).

For student of Group 1a there is an average increase of CO₂ concentration equal to 17% (Table 4) with no noticeable increase in clothing level. While, for students of Group 1a there is an increase of their clothing, on average, by 20% (Table 6).

Table 4 Mean CO₂ concentration and perceived air quality before (prior) and after (post) the start of the feedback.

	No.	CO ₂ (ppm)			Perceived air quality	
		prior	post	%diff	prior	post
1a	1	1023±251	1278±496	+ 22%	Acc.	Acc.
	2	1243±625	1564±634	+ 26%	Very sat.	Very sat.
	3	1064±452	1233±664	+ 16%	Acc.	Very sat.
	4	954±220	1006±231	+ 5%	Acc.	Acc.
1b	5	1314±326	1021±297	- 22%	Acc.	Rather
	6	1272±393	1239±312	- 3%	Slightly dis.	Acc.
	7	1118±439	1207±541	+ 8%	Acc.	Acc.
	8	1032±271	955±214	- 7%	Slightly dis.	Rather
	9	1194±396	1108±333	- 7%	Acc.	Very sat.
	10	1016±248	997±261	- 2%	Rather sat.	Acc.
2	11	1334±423	1342±409	+ 1%	Rather sat.	Acc.
	12	1080±326	961±318	- 11%	Acc.	Acc.
	13	1380±620	1564±698	+ 13%	Acc.	Acc.
	14	1131±496	1072±433	- 5%	Acc.	Acc.
3	15	1048±390	1085±340	+ 3	n.a.	n.a.

Acc.=Acceptable, Sat.= Satisfying, Dis=Dissatisfying, n.a.=not available

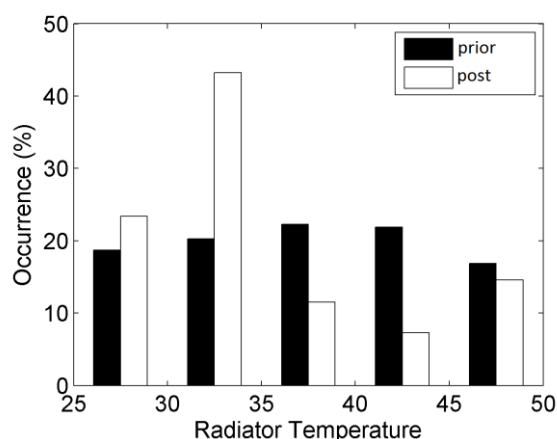


Figure 9 Radiator temperatures before (prior) and after (post) the start of the feedback (Group 1)

An in-depth analysis of CO₂ room concentrations for Group 1a shows that, while student no. 1 and 4 followed the feedback's recommendations to keep CO₂ levels under 1800 ppm, students no. 2 and 3

exceeded the level of 1800 ppm for respectively 30 % and 20 % of the time. This unwanted effect was probably due to the fact that feedback tips were either not seen or ignored. This shows that there is a risk of air quality degradation when trying to save heating energy. This risk needs to be taken into account when designing feedback strategies. At this regard, it is important to notice that the limit of 1800 ppm is higher than the commonly-referenced value of 1000 ppm [46]. However, the adopted value of 1800 ppm (corresponding to a percentage of dissatisfied people equal to 40% [46]) was intended as a critical limit to not be overcome, 1000 ppm still being the optimal limit.

In Table 4, it can be seen that the average CO₂ concentrations before the feedback are generally higher than 1000 ppm, this can be attributed to different facts:

- the low ventilation rates in winter,
- the small dimensions of the room,
- the vicinity of the CO₂ sensor to the occupant since it was not always possible to guarantee a distance of 2m due to the small dimensions of the room.

From the analysis of the clothing levels (Table 6 and Figure 10) it can be noted that Group 2 tended to wear less clothing during the feedback phase. Therefore, they responded to the higher indoor temperatures through decreasing their clothing insulation. This fact confirms the previously hypothesized low interaction with the app.

The average outdoor relative humidity was the same during the first and second experimental phase (83%). The indoor relative humidity was in the recommended range 40%-60% [39]. Humidity was perceived as neutral by the majority of the students, but 4 out of 14 students perceived it as slightly humid (Table 5).

Table 5 Relative humidity and humidity sensation before (prior) and after (post) the start of the feedback; n.a.: not available.

		Relative humidity (%)		Humidity sensation	
		prior	post	prior	post
1a	1	47 ±5	50 ±5	Neutral	Neutral
	2	49 ±6	55 ±5	Neutral	Neutral
	3	43 ±4	44 ±5	Slightly humid	Slightly
	4	44 ±5	46 ±4	Neutral	Neutral
2a	5	43 ±4	42 ±5	Slightly humid	Slightly
	6	48 ±6	48 ±5	Slightly dry	Neutral
	7	51 ±6	51 ±5	Neutral	Neutral
	8	49 ±7	50 ±6	Slightly humid	Slightly
	9	48 ±5	49 ±4	Neutral	Neutral
	10	48 ±5	46 ±4	Neutral	Neutral
2	11	53 ±7	54 ±6	Slightly humid	Neutral
	12	48 ±3	45 ±3	Neutral	Neutral
	13	50 ±6	52 ±9	Neutral	Neutral
	14	45 ±6	44 ±5	Neutral	Neutral
3	15	51 ±5	49 ±5	n.a.	n.a.

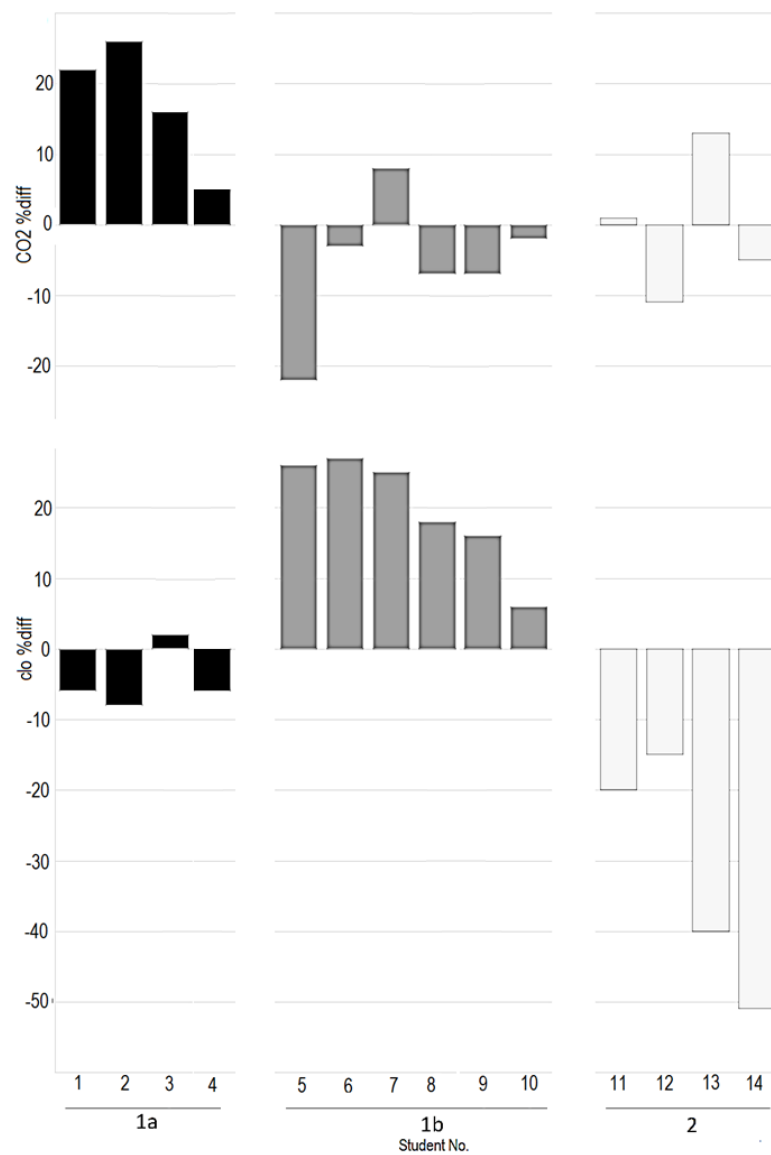


Figure 10 Percentage differences in CO2 concentration (CO2 %diff) and students' levels of clothing (clo %diff) before and after the start of the feedback

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Table 6 Mean room air temperature, thermal sensation and mean clothing level before (prior) and after (post) the start of the feedback.

	No.	Air temperature (°C)			Thermal sensation		Clothing (clo)		
		prior	post	diff	prior	post	prior	post	%diff
1a	1	17.5 ±1.2	18.8 ±1	+ 1.3	Acc.	Rather sat.	0.67	0.63	-6%
	2	21 ±1	21.1 ±1	+ 0.1	Rather sat.	Rather sat.	0.74	0.68	-8%
	3	20.2 ±1.1	19.9 ±1.4	- 0.3	Rather sat.	Very sat.	0.59	0.6	+2%
	4	19.7 ±0.6	19.1 ±0.8	- 0.6	Acc.	Acc.	0.7	0.66	-6%
1b	5	21.2 ±0.7	20.2 ±1.1	- 1	Acc.	Rather sat.	0.73	0.92	+26%
	6	20.2 ±0.7	19.3±0.8	- 0.9	Rather sat.	Rather sat.	0.6	0.76	+27%
	7	18.4 ±1.2	17.7 ±2	- 0.7	Acc.	Acc.	0.36	0.45	+25%
	8	18.3 ±1.3	17.6 ±1.9	- 0.7	Slightly dis.	Rather sat.	0.51	0.6	+18%
	9	20.1 ±1.1	20 ±1.2	- 0.1	Acc.	Very sat.	0.62	0.72	+16%
	10	19 ±0.6	18.9 ±0.5	- 0.1	Rather sat.	Rather sat.	0.64	0.68	+6%
2	11	20.3 ±0.8	20.2 ±1.1	- 0.1	Rather sat.	Rather sat.	0.49	0.39	-20%
	12	19.9 ±0.3	18.9 ±0.9	- 1	Rather sat.	Acc.	0.52	0.44	-15%
	13	21.6 ±0.9	22.2 ±0.9	+ 0.6	Rather sat.	Rather sat.	0.94	0.57	-40%
	14	19 ±1.1	19.7 ±1.2	+ 0.7	Rather sat.	Acc.	0.39	0.19	-51%
3	15	18.5 ±0.6	18.8 ±0.7	+ 0.3	n.a.	n.a.	n.a.	n.a.	n.a.

Acc.=Acceptable, Sat.= Satisfying, Dis=Dissatisfying, n.a.=not available

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4.3 The effects of feedback on psychological variables

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Due to the limited number of surveyed thermal sensation votes, the analysis of the neutral temperatures for each student before and after the start of the feedback was the most difficult task of this study. In fact, as outlined by Nicol and Humphreys [47], the two traditional methods of calculating the neutral temperature (i.e. regression and probit analysis) require a large number of responses to give reliable results.

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The regression method consists in calculating the mean TSV for each 1°C (or 0.5°C) temperature bin and drawing the regression line, the neutral temperature is the one corresponding to “TSV=0” [24, 48]. This method assumes that TSV is linearly dependent from the temperature and that no adaptation takes place. In field studies in homes TSV is never only dependent on air temperature. Since people tend to continually adapt and to have more control over their environment, there are many other factors such as clothing, metabolism, behaviours that affect TSV. TSV and room air temperature tend to interact with each other and are, therefore, not necessarily linearly dependent. This has been previously observed in field studies of Oseland, Nicol, Rijal and Indragranti [47, 49-53]. Furthermore, this approach is not really rigorous since thermal sensation votes are ordinal variables and, therefore, it is not appropriate to calculate their mean [29].

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In this study the regression method did not give robust correlations (e.g. students no. 7-8-9-11 in Table 7) and, therefore, it failed to give reliable values. In fact, for many students the majority of the votes were neutral and, so, the method was not able to predict neutral temperatures.

422 In order to overcome the problems due to the reduced number of responses, Nicol and Humphreys
423 have calculated the neutral temperature using the Griffith method with the following equation:

424
$$T_n = T_m + (0 - TSV_m)/a$$

425 TSV_m is the mean thermal sensation vote,
426 T_m is the mean globe temperature,
427 a is the regression coefficient.

428 We used the regression coefficient 0.25 which is usually obtained in field studies according to Nicol
429 [47] and we calculated the neutral temperature for each student before and after the start of the
430 feedback by computing the mean of the TSVs (Table 7). However, this approach suffers the same
431 limitations of the regression method since it implies that no adaptation takes place and it is based on
432 the calculation of the mean of an ordinal variable [54]. Therefore, we propose a new approach for
433 computing the neutral temperatures and we compare the resulting temperatures with the ones
434 obtained with the two methods described above (regression method and Griffith method, see Table
435 7).

436 The new method uses the corrected TSVs and is explained by the following algorithm:

437 **IF** $\%TSV_{comf} > 80$:
438 **THEN** $T_n = \text{Mean}(T_0)$
439 **IF** $\%TSV_{comf} < 80$:
440 **THEN** $T_n = \text{Mean}(T_{CH})$

441 T_n is the neutral temperature,
442 $\%TSV_{comf}$ is the percentage of comfortable votes (i.e. corrected TSVs between -1 and 1),
443 T_0 are the temperatures for corrected TSV equal to 0,
444 T_{cold} are the temperatures for corrected TSV lower than -1,
445 C is the percentage of corrected TSVs lower than -1,
446 T_{hot} are the temperatures for corrected TSV higher than 1,
447 H is the percentage of corrected TSV higher than 1,
448 T_{CH} are the temperatures comprised between the C_{th} percentile of T_{cold} and the H_{th} percentile of T_{hot}
449 (green lines in Figure 11).

450 In the case of student no. 5 there are not temperatures T_0 between the two percentile of T_{cold} and T_{hot}
451 and, therefore, it is not possible to calculate neutral temperatures with this method (Figure 12).

452 The analysis of the neutral temperatures (Table 7) shows that feedback has potential to directly affect
453 the notion of comfort of occupants and lower students' neutral temperatures. We achieved a
454 reduction of neutral temperature up to 1.7°C for student no. 7 (Figure 11). This also demonstrates
455 that thermal comfort is "a highly negotiable socio-cultural construct" [27] and that real-time feedback
456 can prompt occupants' adaptive behaviour and reshape their notion of comfort. This process of re-
457 defining occupants' notion of comfort can contribute to lower building heating and cooling energy
458 consumption. Of course, this result can only be achieved if there is a sufficient motivation to interact
459 with the app.

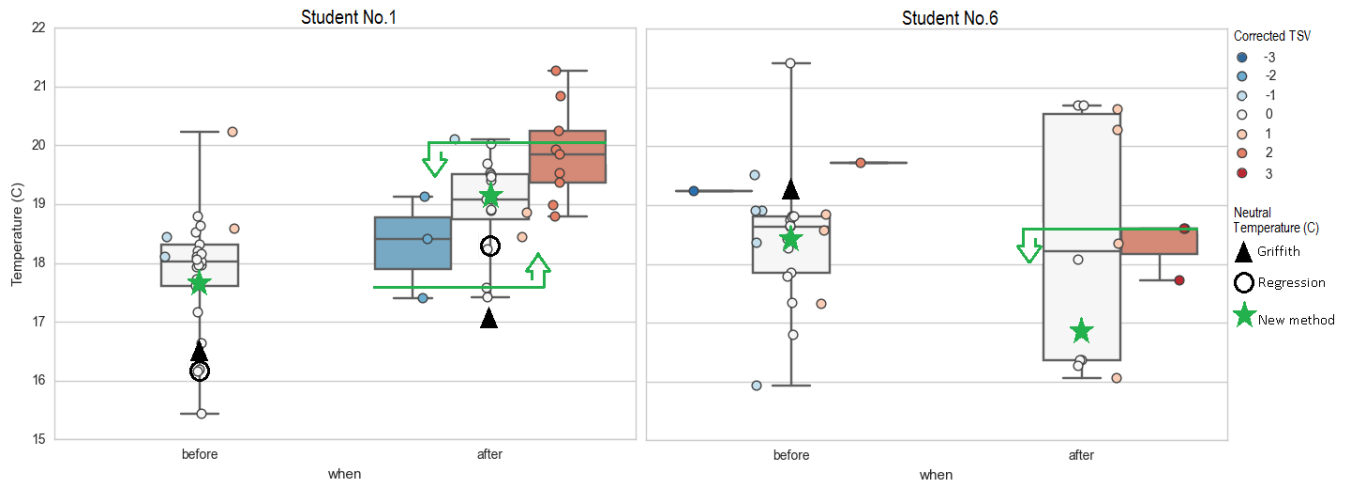


Figure 11 Box plot of neutral and cold temperatures before and after the start of the feedback for students no. 1 and 6. The line within each box is the median, the edges of the box are the 25th and 75th percentiles (indicated respectively as q_1 and q_3), the thin lines (whiskers) extend to those values between $q_3 - 1.5*(q_3 - q_1)$ and $q_1 + 1.5*(q_3 - q_1)$.

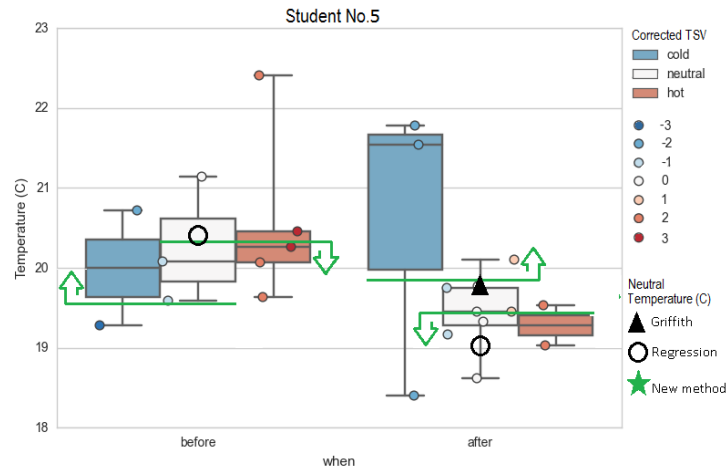


Figure 12 Box plot of neutral and cold temperatures before and after the start of the feedback for students no. 1 and 6. The line within each box is the median, the edges of the box are the 25th and 75th percentiles (indicated respectively as q_1 and q_3), the thin lines (whiskers) extend to those values between $q_3 - 1.5*(q_3 - q_1)$ and $q_1 + 1.5*(q_3 - q_1)$.

Two other important facts can be observed for students of Group 1: (i) overall perceived environmental control increases and (ii) thermal and air quality satisfaction levels increase. The Wilcoxon signed rank test is used in order to analyse differences between the samples before and after the start of the feedback. A non-parametric test is chosen due to the limited sample size and due to the fact that the sampling distribution is non-normal. The selected significance level is $p = 0.05$. For Group 1, perceived control levels for temperature and air quality are significantly higher (respectively, $W=8$, $p=0.046$ and $W=0$, $p=0.005$) after the start of the feedback (Median=3) than before (Median=2.5). Thermal satisfaction levels are significantly higher after the start of feedback (Median=4) than before (Median=3), $W=0$, $p=0.0049$. Satisfaction levels for air quality are also significantly higher after the feedback (Median=3.5) than before (Median=3), $W=7$, $p=0.036$.

479 *Table 7 Neutral temperatures calculated with three different methods (Griffith, Regression, New) before (prior) and after*
 480 *(post) the start of the feedback; n.a.: not available.*

No.	Griffith method		Regression method				New method		
	prior	post	prior	R^2	post	R^2	prior	post	diff
1	16.5	17.1	16.3	0.8382	18.4	0.8165	17.6	19.2	1.6
2	21.7	21.8	22.0	0.4595	16.5	0.0535	21.2	21.3	0.1
3	21.1	22.1	20.5	0.7598	20.6	0.2328	20.8	21.3	0.5
4	21.1	20.6	20.2	0.4808	21.8	0.3683	19.9	19.5	-0.4
5	23.1	23.6	22.7	0.4234	21.5	0.6337	21.5	21	-0.5
6	17.6	19.7	20.4	0.3455	19.1	0.0761	n.a.	n.a.	n.a.
7	19.4	14.5	15.0	0.0492	41.4	0.0007	18.5	16.8	-1.7
8	20.9	22.7	13.8	0.0725	5.7	0.0857	18.1	19.7	1.6
9	20.5	20.2	19.6	0.0245	20.1	0.5348	20.4	20.1	-0.3
10	18.8	19.2	19.8	0.4227	18.7	0.6519	19	18.9	-0.1
11	20.7	20.4	18.7	0.0575	15.2	0.0012	20.7	20.6	-0.1
12	19.6	21.8	19.6	0.9269	5.6	1	19.9	20.2	0.3
13	23.5	22.7	20.8	0.3273	23.1	0.0582	22.1	22.7	0.6
14	19.3	26.8	21.9	0.4899	21	0.9317	19.3	20.9	1.6

481 *Table 8 Overall perceived control before (prior) and after (post) the start of feedback; n.a.: not available.*

	No.			
		prior	post	diff
1a	1	30	70	+ 40
	2	50	50	0
	3	60	60	0
	4	50	50	0
1b	5	60	70	+ 10
	6	50	50	0
	7	50	60	+10
	8	60	70	+ 10
	9	50	80	+ 30
	10	50	50	0
2	11	40	30	- 10
	12	70	70	0
	13	60	60	0
	14	50	50	0
3	15	n.a.	n.a.	n.a.

482 **5. Limitations**

483 Proving the efficacy of feedback in changing occupant behaviours is not an easy task. Therefore, in
 484 common with many other studies in this field, we discuss the following limitations of our work:

- **Fallback effect:** This is the phenomenon where “newness” motivates people to change but this motivation vanishes with time [55]. We monitored the effect of feedback for only 3 weeks and conclusions cannot therefore be drawn about their long-lasting effect.
- **Sample size:** The reduced sample size is another limiting factor of this study. Since this work was designed as a precursor to a more in-depth study involving more real homes over a longer period of time, it may be seen as “proof-of-concept” that real-time context-aware feedback *could* have an impact on occupant adaptive behaviours and neutral temperatures, and thus meriting further investigation.
- **Hawthorne effect:** This is a phenomenon where people behave differently when they know they are being observed. In this study, we tried to minimize this effect by avoiding instructions on how to use the application. The app was introduced to the students as a tool that they could use to reduce their heating energy use without any additional information on its efficacy. However, as with the fallback effect, only a long-term study is likely to address this problem.

Since the feedback provided includes suggestions for lowering internal temperature, this could potentially have an impact on occupant health especially with older occupants. However, we mitigate this effect by focusing the feedback on temperature ranges within the acceptable band of 18 – 21°C as suggested by [56].

Finally, this experiment is mainly focusing in detecting changes in thermal comfort variables, namely adaptive actions, neutral temperatures and perceived environmental control. Therefore, results and conclusions of this paper focus on reporting and quantifying those changes, and not other variables such as energy use.

6. Conclusions

This study aimed to detect and quantify changes in occupants’ adaptive responses, neutral temperatures and perceived environmental control as results of the feedback intervention. From the analysis of the monitored data, it emerges that feedback has the potential to prompt “good” adaptive behaviours such as wearing more clothes and better controlling the use of windows for ventilation, but it also reveals that a risk of high indoor CO₂ levels exists and that, therefore, this problem needs to be carefully addressed when designing feedback strategies. This study also confirms the importance of perceived control in defining thermal comfort and shows that the degree of occupant’s control over the environment depends not only on the characteristics of the building and of its systems (building contextual factors) but also on occupant’s awareness of them. Subjects felt they had greater control over their thermal environment and, consequently, this greater control was able to mitigate their thermal expectations and offset possible discomforts due to the lower temperatures. Given a sufficient motivation for interacting with the application, real time feedback can effectively and positively contribute to guiding occupants’ adaptive actions towards energy-aware behaviours without negatively affecting their satisfaction. The results of this study therefore demonstrate that saving energy does not always mean sacrificing occupant comfort.

7. Acknowledgments

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